1 Wireless Communications and Networking with Unmanned Aerial Vehicles: An Introduction

The past few years witnessed a major revolution in the area of unmanned aerial vehicles (UAVs), commonly known as drones, due to significant technological advances across various drone-related fields ranging from embedded systems to autonomy, control, security, and communications. These unprecedented recent advances in UAV technology have made it possible to widely deploy drones across a plethora of application domains, ranging from delivery of goods to surveillance, environmental monitoring, traffic control, remote sensing, and search and rescue. In fact, recent reports from the Federal Aviation Administration (FAA) anticipate that sales of UAVs may exceed seven million in 2020, and many industries are currently investing in innovative drone-centric applications and research. To enable all such applications, it is imperative to address a plethora of research challenges pertaining to drone systems, ranging from navigation to autonomy, control, sensing, navigation, and communications. In particular, the deployment of UAVs in tomorrow's smart cities is largely contingent upon equipping them with effective means for communications and networking. To this end, in this book, we provide a comprehensive treatment of the wireless communications and networking research challenges and opportunities associated with UAV technology. This treatment begins in this chapter, which provides an introduction to UAV technology and an in-depth discussion on the wireless communication and networking challenges associated with the introduction of UAVs.

1.1 Brief Evolution of UAV Technology

A UAV is, in essence, an unmanned aircraft or robot that can fly in nearly unconstrained locations either autonomously or while being remotely controlled by an operator. In the early twentieth century, UAV technology was mostly restricted to military environment. For instance, many references [1–4] trace back the origin of drones to the nineteenth century when unmanned balloons were used to bomb the city of Venice in Italy. Then, after some failed or unused UAV-like experiments (such as the US Army's Kettering Bug [5]) in the early 1900s, military UAV technology started to improve and evolve during the Second World War and throughout the Cold War. These early attempts at providing unmanned aircrafts were mostly restricted to well-defined and

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very confined military missions, such as reconnaissance or combat surveillance. Despite their restricted application space, these early developments in UAV technology provided an important foundation for the modern-day commercial drone revolution, which really started in the mid-2000s when new applications of UAVs, such as disaster relief, search and rescue, and infrastructure inspection, began to take shape, driven by a number of governments. Meanwhile, the first commercial UAV permit was issued in 2006. Following this event, the French company Parrot produced their Parrot AR Drone in 2010, which was arguably one of the first UAVs ready to be operated by end-users using a WiFi connection and a smartphone. The Parrot AR Drone was an important first step toward popularizing the idea of consumer-operated drones that can be employed for recreational as well as commercial purposes.

However, the true catalyzer for the UAV technology was Jeff Bezos' 2013 announcement about his intentions to deploy a UAV-based delivery system for Amazon. This announcement was also followed by similar ideas from other major companies such as Google, who debuted their drone-delivery Wing project in 2014. Since then, the interest and investment in UAV technology for commercial applications began an exponential growth both in terms of applications and technology. Most recently, UAVs have become inherently equipped with important communications, computer vision, and machine learning techniques that turned them into truly autonomous and multipurpose devices. This, in turn, led to a surge of new startups, research, and standardization efforts focused on the multifaceted technological and social challenges of UAV technology. These research efforts are rapidly culminating in major breakthroughs across multiple application domains. It is, therefore, inevitable to envision that the next five years or so will witness some of the first real-world deployments of drones across various sectors in the global economy. Such deployments will range from the initial introduction of drone-delivery systems in the near term to a wide-scale deployment of UAV-based autonomous, flying taxis in the long term.

These rapid recent developments in UAV technology have naturally led to many research problems that cut across multiple fields, including navigation, control, machine learning, and communications. In particular, the ability of UAVs to fly in nearly unconstrained locations, coupled with their flexibility and agility, makes them particularly appealing for wireless communications applications. Indeed, communications and networking provide one of the most important emerging applications for UAVs; thus, it is essential to investigate the challenges and opportunities brought forward by UAVs in this domain. The wireless communications and networking applications and challenges of UAVs naturally depend on the type of UAV and associated government regulations. As a result, next, we first provide a classification of UAVs depending on their types and then delve into the wireless communications and networking challenges and opportunities.

1.2 UAV Types and Regulations

Prior to delving into the wireless communications challenges of UAVs, we first provide an overview on the different types of UAVs available as well as recent regulatory progress regarding their deployment.

1.2.1 Classification of UAVs

In general, the terms “UAV” and “drone” can be used to refer to any type of flying, unmanned robot that can be remotely controlled and has multipurpose functions. However, depending on the application, one can choose different types of UAVs, while taking into account their capabilities (e.g., sensors, size, weight, battery life, etc.) and their flight abilities (e.g., altitude, ability to hover, etc.). Although one can provide different ways to classify UAVs, one initial classification can be done based on the flight altitude of the UAVs and their size. In particular, UAVs can be generally grouped into two key categories: low-altitude platforms (LAPs) and high-altitude platforms (HAPs). LAPs are usually small-sized UAVs that can fly at low altitudes that range from tens of meters up to a few kilometers. LAPs are able to move rapidly and are very flexible in their deployment. For instance, most UAVs that have been recently considered in end-user and commercial applications are essentially LAPs. Examples of LAPs include the previously mentioned Parrot AR Drone as well as the popular DJI Phantom drone series. According to the FAA, LAPs will be allowed to fly without permit for a maximum altitude of 400 ft. To exceed this altitude, LAP operators must seek special permissions from the FAA [6].

In contrast to the small and flexible LAPs, HAPs are larger and more capable UAVs that are used to fly at high altitudes (typically above 17 km). HAPs are often quasi-stationary and used for long-term mission purposes. Prominent examples of HAPs include Airbus’ Zephyr [7], which is a stratospheric UAV that can operate as a pseudo-satellite while harnessing solar energy, and Google’s Project Loon [8], a HAP balloon that can be placed at an altitude of 18 km to provide long-term wireless connectivity to rural areas. HAPs are generally much larger and much more enduring than LAPs; thus, they can be deployed for longer-term, satellite-like missions. Meanwhile, LAPs are more appropriate for time-sensitive missions due to their ability to quickly deploy and move. In general, HAPs can be operated continuously for up to a few months of continuous operations (and even longer if energy limitations are overcome). In contrast, current LAP technology limits their continuous operation to a few hours (depending on battery capability and ability to recharge if needed). Naturally, HAPs are also more costly than LAPs.

Both HAPs and LAPs can be further categorized depending on the type of robot/drone being used, as shown in Figure 1.1. For instance, LAPs can be further grouped into fixed-wing, rotary-wing, and balloon UAVs. Compared to rotary-wing UAVs, fixed-wing LAPs, such as small aircrafts, have a higher weight and speed, and they are able to remain aloft by moving forward. In contrast, rotary-wing UAVs have the ability to hover over a specific geographical area while remaining stationary if needed. Meanwhile, HAPs can be further grouped into airships, aircrafts, and balloons. Airships are the largest type of HAPs, and they have significant power and load capabilities. They are often deployed in a quasi-stationary manner for long-term continuous missions (up to a few years). HAP balloons, on the other hand, are relatively lightweight HAPs that can operate for a few months continuously. They are deployed primarily for stationary missions. Moreover, aircraft HAPs are also lightweight; however, in contrast to balloons, they can fly and move around an area (typically flying in a circle and in a less

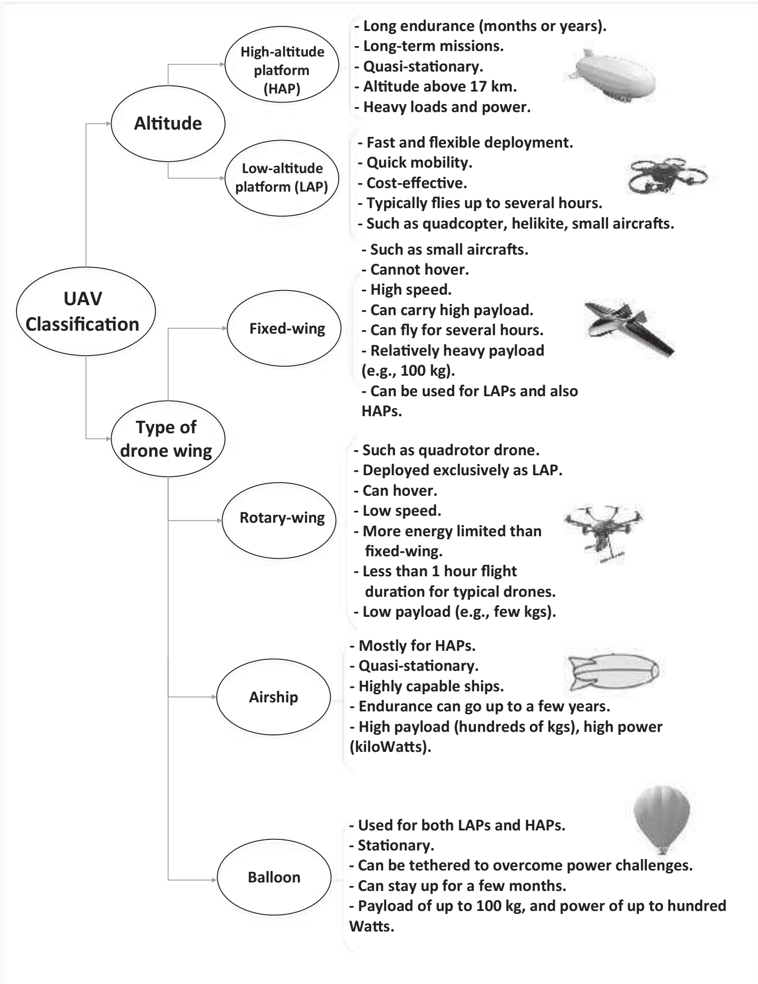

Figure 1.1 Classification of UAVs.

flexible manner than HAPs). HAP aircrafts are also suitable for missions of up to a few months.

As will be evident from the subsequent chapters of this book, both HAPs and LAPs, in their various categories, will play important roles in wireless communication scenarios. Indeed, the various features of LAPs and HAPs exposed in Figure 1.1 will naturally impact the role they will take from a wireless and networking perspective.

1.2.2 UAV Regulations

The application domains of UAVs is not only limited by their types, but it is also constrained by potential regulations that various governmental agencies may impose. For instance, although the application domain of UAVs includes countless use cases, these use cases are accompanied by various privacy, public safety, security, collision

Table 1.1 Initial regulations for the deployment of UAVs without any specific permit.

Country	Maximum altitude	Minimum distance to people	Minimum distance to airport
United States	122 m	N/A	8 km
Australia	120 m	30 m	5.5 km
South Africa	46 m	50 m	10 km
United Kingdom	122 m	50 m	N/A
Chile	130 m	36 m	N/A

avoidance, and data restrictions and concerns. To handle these concerns, numerous efforts have recently emerged to provide regulations to control the use and operation of UAVs while taking into account their types and capabilities. For regulatory purposes, five key criteria are often considered [9, 10]:

1 *Applicability*: applicability involves specifying the scope (considering type, weight, and role of UAVs) within which certain regulatory rules will be applied.
2 *Operational limitations*: these include restrictions on the locations where UAVs can fly or operate. For instance, many European cities, such as Helsinki in Finland, have recently designated various areas as no-fly zones for UAVs. Such location constraints naturally impact all sorts of applications in which UAVs will be used.
3 *Administrative procedures*: these include precise, legal processes that must be put in place in order to deploy and use a UAV.
4 *Technical requirements*: these include constraints on the communications, control, and mechanical capabilities of drones.
5 *Ethical constraints*: in order to operate UAVs (and any other autonomous systems), it is imperative to introduce ethical considerations that must be followed by UAV operators. Such considerations include ways to protect the privacy of generated data and the way in which a UAV can be used in commercial and military scenarios.

UAV regulations vary between different countries and types of geographical areas (e.g., urban or rural). In the United States, regulations for UAV operations are issued by the FAA and National Aeronautics and Space Administration (NASA). For instance, NASA is planning to develop UAV control frameworks in collaboration with the Federal Communications Commission (FCC) and the FAA. The FCC is currently investigating if a new spectrum policy needs to be established when operating drones for communication purposes. In Table 1.1, we list a number of UAV regulations in various countries [9]. All such regulations must be accounted for when treating UAV-related research problems, particularly communication problems.

1.3 Wireless Communications and Networking with UAVs

UAVs, in all of their types and sizes, provide ample opportunities for wireless communication applications. In general, all types of UAVs can be equipped with wireless interfaces. Such interfaces can operate at either unlicensed, WiFi frequencies or

Table 1.2 UAV networks versus terrestrial networks.

UAV Wireless Networks	Terrestrial Wireless Networks
• Spectrum is scarce.	• Spectrum is scarce.
• Three-dimensional network models.	• Mostly two-dimensional network models.
• Inherent ability for line-of-sight communication due to altitude.	• Difficulty to maintain line-of-sight.
• Elaborate and stringent energy constraints and models.	• Well-defined energy constraints and models.
• High dynamics due to high mobility.	• Mobility confined to a few models (e.g., pedestrians, cars, etc.).
• Hover and flight time constraints.	• No inherent timing constraints.

licensed, cellular frequencies. Naturally, equipping UAVs with wireless communications capabilities will pave the way for a plethora of new application domains for UAV technologies. Across these application domains, we can see three primary communication roles for UAVs: (a) UAVs as aerial base stations (or access points) that can be deployed to provide wireless networking and communications capabilities to various geographical areas, (b) UAVs can leverage existing infrastructure (e.g., cellular or WiFi) to communicate with one another or with ground devices, and (c) UAVs can be deployed as aerial relays that can provide an extension to the coverage and connectivity of existing wireless infrastructure. Across all those three roles, as summarized in Table 1.2, one can identify a number of key technical differences between conventional networks, terrestrial wireless networks, and wireless networks that must support UAVs.

For each one of the three use cases, various research challenges must be overcome, as discussed next.

1.3.1 UAVs as Flying Wireless Base Stations

The first natural use case for UAVs in communication applications is the flying base station (BS) case. In this use case, the UAV itself is used as a provider of wireless communication services. For instance, LAPs can be used to provide on-demand wireless networking capabilities to areas that lack coverage or that are currently congested, such as hotspot areas. Indeed, the flexibility and agility of LAPs allows network operators to use them for providing rapid and on-demand connectivity whenever needed. Meanwhile, HAPs can be deployed for longer-term wireless coverage purposes. In fact, HAPs are a central component of most recent proposals for providing connectivity to rural areas (e.g., Google's Loon project). This is due to the fact that HAPs can remain flying for long periods of time and, thus, can provide continuous broadband services to rural or remote areas in which ground wireless infrastructure is sparse or hard to deploy. Moreover, by jointly using LAPs and HAPs as flying base stations, one can construct a multitier three-dimensional (3D) wireless network that incorporates both short-term and long-term coverage solutions. Such a fully fledged UAV-based wireless network is

Table 1.3 UAV base station versus terrestrial base station.

UAV Base Stations	Terrestrial Base Stations
• Deployment is naturally three-dimensional.	• Deployment is typically two-dimensional.
• Unique propagation environment with scarcely available models.	• Well-established models for the propagation environment.
• Short-term, frequently changing deployments.	• Mostly long-term, permanent deployments.
• Mostly unrestricted locations.	• Few, selected locations.
• Mobility dimension.	• Fixed and static.

envisioned to be an important stepping stone toward delivering global wireless connectivity. A summary of the key differences between terrestrial BSs and UAV-based BSs is shown in Table 1.3.

Naturally, designing a wireless network that relies on flying UAV BSs (LAPs or HAPs), brings forward a number of unique research challenges and opportunities that stem from the unique features of UAV BSs shown in Table 1.3:

- The deployment of flying BSs is, by nature, done in 3D space. Indeed, the altitude dimension provides a new degree of freedom that a network operator can exploit to enhance connectivity, such as by establishing line-of-sight (LOS) links between flying BSs and ground users. However, the flying nature of UAV BSs also brings in new research challenges, such as the need for dynamically optimizing their deployment locations as well as managing their mobility.
- The air-to-ground wireless channel presents a new propagation environment whose characteristics can significantly differ from conventional terrestrial channel models (e.g., Rayleigh models). Indeed, propagation modeling and measurements are an important research challenge for UAV BSs. Along those same lines, there is a need for realistic air-to-air channel models (e.g., for communication between multiple UAVs of possibly different types) in order to deploy a fully fledged wireless cellular network that leverages UAVs. We do note that propagation challenges are not restricted to the UAV BS role, but they are pervasive across all wireless communication roles of UAVs.
- When dealing with UAV BSs, it is imperative to explicitly take into account the dynamics (e.g., control), mobility, and flight constraints of the UAVs. For instance, depending on their class (HAP or LAP) and type, UAVs can have different battery and power capabilities. These capabilities will directly impact the quality-of-service (QoS) that these UAVs can provide when servicing wireless users. For example, the hover time constraints of rotary-wing LAPs will impose a maximum wireless service time that such UAVs can deliver for a given geographical area. As such, characterizing the performance of a wireless network that relies on UAV BSs must explicitly factor in these UAV-specific constraints.
- Resource management in a network with UAV BSs differs substantially from resource management in classical cellular networks. On the one hand, the aforementioned flight constraints provide new resources (e.g., flight time, on-board energy) that must

be managed along with conventional wireless resources (e.g., spectrum). On the other hand, the ability of UAVs to fly and hover brings forward a unique opportunity to leverage high-frequency bands (e.g., millimeter wave) that can benefit from the ease with which UAVs can establish LOS connections. As a result, the design of new resource management schemes that are cognizant of these unique features of UAV BSs is a very important research challenge.

1.3.2 UAVs as Wireless Network User Equipment

To enable the various UAV applications previously mentioned, UAVs must be able to communicate with existing wireless networks, such as cellular or WiFi networks. In such scenarios, UAVs act as user equipment (UE) of the wireless network. When UAVs are used as UAV UEs of a ground wireless cellular network, they are often referred to as cellular-connected UAVs. Cellular-connected UAV UEs will enable a myriad of new application domains in which communications between UAVs and a ground cellular infrastructure is necessary for the UAVs to deliver application-specific data, to acquire control information, and to achieve the objective of their mission. Examples of such applications include delivery drones, real-time surveillance and multimedia transmission, and UAV-assisted transportation networks [11]. As discussed in the UAV BS case, the introduction of aerial UAV UEs that fly in unrestricted locations and communicate in 3D space, will lead to unique wireless networking challenges that are not dealt with in a ground network. In particular, deploying cellular-connected UAV UEs requires overcoming some of the following key challenges:

- Managing network interference becomes much more challenging when UAV UEs are deployed. This is due to the fact that flying UAV UEs will now generate LOS interference on ground BSs and ground UEs, which can potentially lead to significant performance degradation. As such, it is necessary to introduce new interference management solutions that are cognizant of the unique, 3D properties of UAV UEs and their capabilities.
- Current wireless infrastructure has been designed to maximize the performance of ground users. As a result, many design choices have been made without accounting for the possibility of having flying users. For example, current cellular network BSs have been developed in a way to maximize antenna coverage to the ground. As a result, current BSs will have their antennas tilted downward toward the ground. Consequently, these BSs cannot serve flying UAV UEs using their main antenna lobe and will have to rely on their side or back lobes. Hence, optimizing antenna usage for coexisting aerial and ground UEs is a key challenge for wireless communication with cellular-connected UAV UEs.
- For mission-critical applications such as delivery drones, the UAVs will need to use the cellular infrastructure to receive status information and control data. Such data will be very time sensitive and critical, and, thus, there is a need to develop new

techniques to guarantee low latency, reliable communications among UAV UEs, and ground cellular infrastructure.

- Given the difference in the propagation environment between ground users and UAV UEs, a network operator must design new techniques to identify ground and aerial users. Identification becomes particularly challenging when a terrestrial device (e.g., a smartphone) is attached to a UAV to act as a UAV UE. In such a case, the network cannot rely on traditional authentication or reporting mechanisms, and, thus, new identification techniques are needed. Performing device identification is a necessary step toward properly integrating UAV UEs into cellular systems, since it will allow the system to better map aerial and ground interference and then perform proper resource optimization and management.
- Most UAV-based systems plan the trajectory of their UAVs based on the specific mission objectives. In fact, it is very common to optimize the trajectory of UAVs in a way to minimize the mission time. However, when UAVs are deployed over a wireless network as UAV UEs, their trajectory will not only affect the mission objectives, but it will also impact the performance of the wireless network. For example, if the trajectory of a given UAV UE passes through many ground BSs, it may cause substantial LOS interference to those BSs and degrade the QoS of the wireless system. Hence, it is necessary to develop new wireless-aware trajectory optimization solutions that can balance the various objectives of a UAV system, including mission objectives and wireless network performance.
- Along with trajectory optimization, handover and mobility management are also two prominent technical challenges for cellular networks with UAV UEs. These challenges will be significantly exacerbated by the fact that the mobility of UAV UEs is much more dynamic than that of ground devices. In particular, the diversity of paths and locations that UAV UEs can visit, along with their 3D nature, will bring forward new mobility management challenges that are not dealt with in ground cellular systems.
- As is the case for the UAV BS scenario, UAV UEs will also face challenges pertaining to the aerial propagation environment as well as the need for dynamic resource management.

1.3.3 UAVs as Relays

The third use case scenario for UAVs in a wireless environment is one in which the UAVs act as relay stations that provide a relaying link between a transmitter and a receiver. In particular, the use of UAV relays is suitable for enhancing the coverage of a ground network or for overcoming obstacles (e.g., high hills or high-rise buildings) that can prevent the possibility of LOS communication between a transmitter and a receiver. The use of UAV relays has also been particularly popular for providing connectivity among the ground users of mobile ad hoc networks. Another important application for UAV relays is the use of a flying ad hoc network to provide backhaul connectivity to a ground wireless or cellular users. In UAV relay use case scenarios, the UAV will act as a transceiver that receives data from a ground device and then relays this data (via one or more hops) to other devices. While deploying UAV relays shares many challenges with the UAV BS and UAV UE cases, it also has its own unique challenges:

- To perform proper relaying, UAVs must rely on well-designed cooperative communication mechanisms. For instance, UAVs can potentially adopt classical cooperative relaying schemes, such as amplify-and-forward or decode-and-forward. However, the fundamental performance limits of such mechanisms were mostly studied for ground networks, and, hence, there is a need for a more comprehensive analysis on the relaying performance of flying, UAV-based networks. In addition, more advanced relaying mechanisms will also be needed to cope with unique features of UAVs, such as their mobility and dynamics.
- For proper relaying, UAVs will need to coordinate their positioning and potential transmission. To do so, the UAVs must rely on their control system. As a result, there is a need for new communication and control codesign mechanisms that can take into account, jointly, the performance of the control and communication systems. Such mechanisms will also be able to account for exogenous factors, such as wind, which can affect the performance of UAV relays. Here, it is noteworthy to mention that joint communications and control problems are also relevant for the UAV BS use case.
- The use of relaying will require UAVs to establish multi-hop communication links in the air. The formation and optimization of such multi-hop, airborne networks is a major research challenge when UAVs act as relays. For instance, given that the air-to-air link is not yet well understood, it is challenging to design dynamic routing and multi-hop communication algorithms that can adapt to this link's propagation environment. Moreover, the development of scaling laws tailored toward the flying nature of multi-hop UAV relays will also be needed to understand the performance limits of a flying multi-hop UAV network.
- The use of HAPs for relaying can also be an interesting research challenge. HAPs provide stable connections and, hence, can potentially help in relaying data from ground users and from LAPs. However, given the long distances over which HAPs, LAPs, and users will communicate, the design of power-efficient and reliable communication methods will be needed.

1.4 Summary and Book Overview

Clearly, deploying UAVs for wireless networking purposes brings in a plethora of challenges, use cases, and opportunities. In the rest of this book, we will explore those challenges and associated problems, while focusing on the following themes:

- In Chapter 2, we provide an in-depth overview of the various applications in which UAVs can be used for communication purposes. This overview will then drive the different research questions that follow in subsequent chapters.
- In Chapter 3, we focus on the physical layer aspects of UAV communications, particularly on radio propagation and waveform designs for aerial wireless users.

- In Chapter 4, we provide a rigorous performance analysis of wireless networks with UAVs, while focusing on the achievable network performance in terms of coverage, rate, and other related QoS metrics.
- In Chapter 5, we focus on the deployment of UAVs (particularly UAV BSs), and we study a number of problems for optimally deploying UAVs while optimizing wireless networking metrics.
- In Chapter 6, we turn our attention to issues of mobility management and, particularly, wireless-aware path planning for communication networks with UAV UEs.
- In Chapter 7, we introduce comprehensive frameworks that enable the optimization of wireless network resources (e.g., spatial, spectral, or temporal resources) while taking into account the unique features of UAV BSs and UAV UEs.
- In Chapter 8, we study the problem of cooperation among UAVs, and we also investigate how coordinated transmissions can be leveraged to improve wireless communication performance with UAV UEs.
- In Chapter 9, we provide a panoramic and practical overview on how mobile technologies, such as long-term evolution (LTE) wireless cellular systems and the emerging fifth-generation (5G) new radio networks, can support UAVs.
- In Chapter 10, we conclude this book by delving into the security of UAV networks. In particular, we discuss a number of frameworks to mitigate prominent cyber attacks that can target UAV systems, particularly UAV systems that are equipped with communication capabilities.

Notations: In the rest of this book, given that each chapter is self-contained and develops comprehensive analytical models for the treated research problems, the notations used in each chapter are specific to that chapter and do not extend to other chapters.